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A USN Diagnostic and Prognostic Development Strategy for Propulsion and Mechanical Systems

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AIR 4.4.2

Propulsion & Power Diagnostics

Naval Air Warfare Center

Patuxent River, MD

Outline

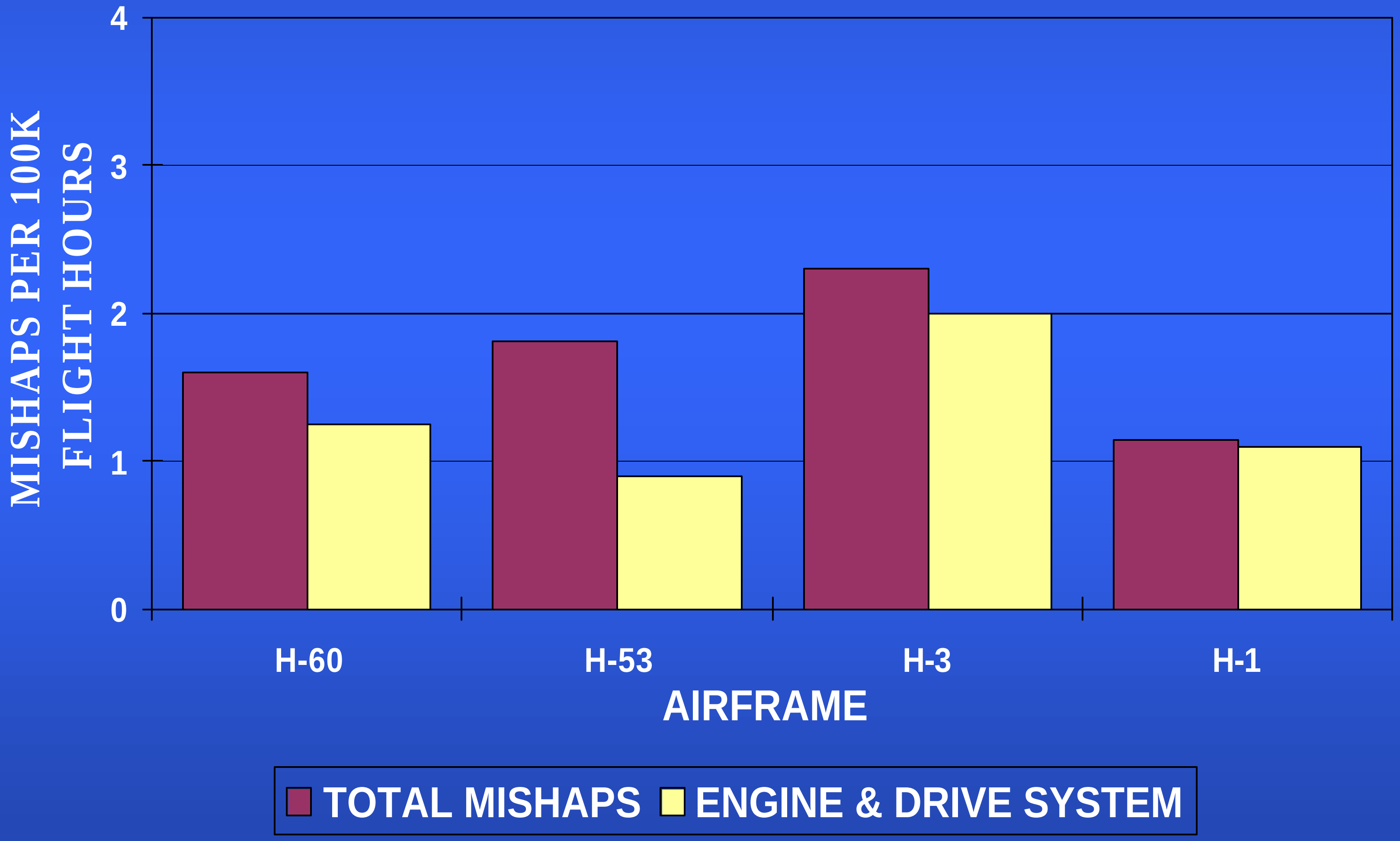
- Overarching Goals
- HTTF Facility Description
- Diagnostics vs. Prognostics
- Seeded Fault and Case Histories
- Conclusions
- Future Plans

Program Goals

- Survey state of the art aircraft diagnostics monitoring systems and leverage lessons learned from users
- Integrate available low risk monitoring technologies into a single, comprehensive on-board system for flight evaluation
- Use unique Helicopter Transmission Test Facility (HTTF) to document and evaluate system capability to detect component faults through very intensive seeded fault testing
- Transition system to fleet end users, support and mature
- Fully develop and demonstrate predictive aspects of prognostics

USN MISHAP DATA
CLASS “A” MISHAPS

CY80-CY90 - BREAKDOWN BY AIRFRAME



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Helicopter Transmission Test Facility (HTTF)

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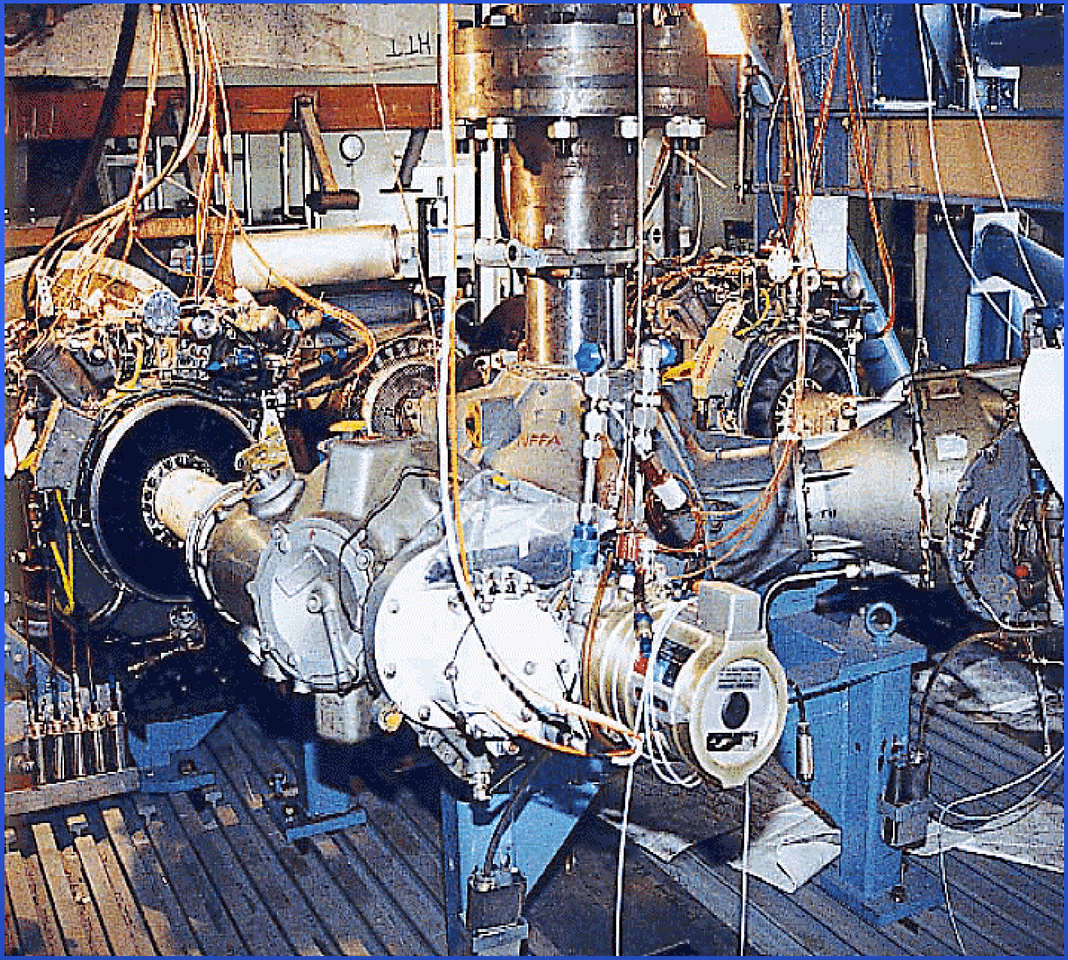
SH-60 Drive System Config:
- Two T700 Engines
- Dual Engine Ops and OEI
- 38000 Series Main Gearbox
- Input Modules
- Accessory Modules
  - Generators
  - Hydraulic Pumps
- Tail Drive System
  - Oil Cooler, IGB, TGB, Shafting & Rotor Brake

Aircraft Loads Simulated
- Main Rotor Load - 8,000 SHP
- Main Rotor Lift - 50,000 #
- Main Rotor Bending - 5,000 #
- Tail Rotor Load - 700 SHP
- Accessories
- Rotor Brake

"Diagnostics Laboratory"



Diagnostics vs. Prognostics

- Diagnostics: the ability to detect and (sometimes) isolate a faulted component and/or failure condition
- Prognostics: the capability to provide early detection and isolation of the precursor and/or incipient fault condition, and to have the technology and means to manage and predict the progression of the fault to component failure

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Predicting Health (Prognostics)

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Health Monitor

Health Trend

Useful Life Prediction

Actions ?

What is the Condition Now?

In Flight?

On the Ground?

Has the Condition Changed?

Changed Relative to What?

How Long Will the Assembly Continue to Carry the Load?

Maintainer?

Increase Surveillance ?

Air Crew?

Order Parts ?

Land?

Continue ?

Inspect ?

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Prognostics
Tool Kit or "Bag of Tricks"

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- Accurate/sensitive sensors, algorithms, indicators
- Multiple indicators and analysis
- Model based techniques
  - Detailed understanding of the physical system
  - Normal and degraded failure conditions
- Determination of component health at any point in time
- Impact of secondary component damage
- Techniques for data scatter and false alarms
  - Fuzzy logic, neural networks, AI
  - Data/Information fusion
- Reasoners

Vibration Based Prognostics

- Using diagnostic algorithms and techniques
- **Intelligent setting of alarm thresholds**
  - **Cockpit and maintenance**
- **Elimination of false alarms**
- Must “see” incipient fault or precursors to component failure
- Extrapolation of vibe frequency data, diagnostic indices and statistical data enabling trending and failure predictions
- Need to understand failure progression rates
  - Experience knowledge base of actual failures
  - “Seeded fault” data base
  - Accurate models

Predictive Prognostics

Failure Progression Timeline

Prognostics

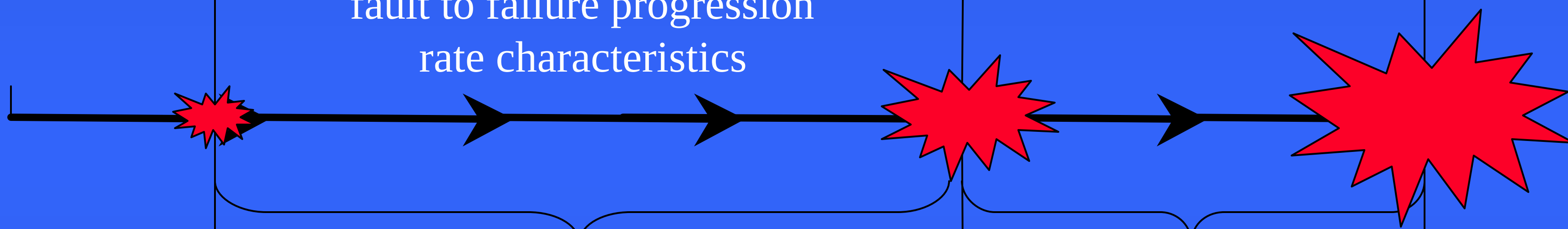
Very early incipient fault

Need: Understanding of fault to failure progression rate characteristics

Diagnostics

System, Component, or Sub-Component Failure

Secondary Damage, Catastrophic Failure



Predicted useful life remaining

Determine effects on rest of aircraft

Have: Better sensors and analysis to “see” early incipient fault

Develop: Useful life remaining prediction models – physics and statistical based

Apply: Better models to determine failure effects across subsystems

Notional strategy to demo predictive prognostics on helo drivetrain

- Identify and Target Components and Sub-elements suitable for Prognostics
  - Those with understandable fault to failure progression characteristics
  - Eliminate those impossible or too hard to consider

- Develop and/or Obtain advanced models
  - Fault to failure progression characteristics
  - Useful life remaining

- Perform experimental seeded fault tests
  - As many as affordable
  - Try to understand the physics of the failure

- Verify and validate models
  - Using seeded fault and blind test data

- Modify useful life remaining prediction model to account for real world considerations
  - Mission Profiles

Seeded Faults and Diagnostic/Prognostic Case Examples

Seeded Faults

- Conducted at HTTF as part of HIDS program
- Specifically targeted to address major reliability and safety areas

Intermediate Gearbox
Root Bending Fatigue Detection

- Root Bending Fatigue Failure is a classic, catastrophic gear failure mode
- Cause of Class A mishaps and loss-of-life in other aircraft models
- HIDS Program goals to (1) demonstrate early detection using model based diagnostics and (2) understand crack propagation subtleties of different gear forms
- EDM notch (.040”D x .006”W x .25”L) implanted into pinion tooth root. Test at 100% tail power for 9 hr.

IGB Input Pinion Root Bending Fatigue Failure Details

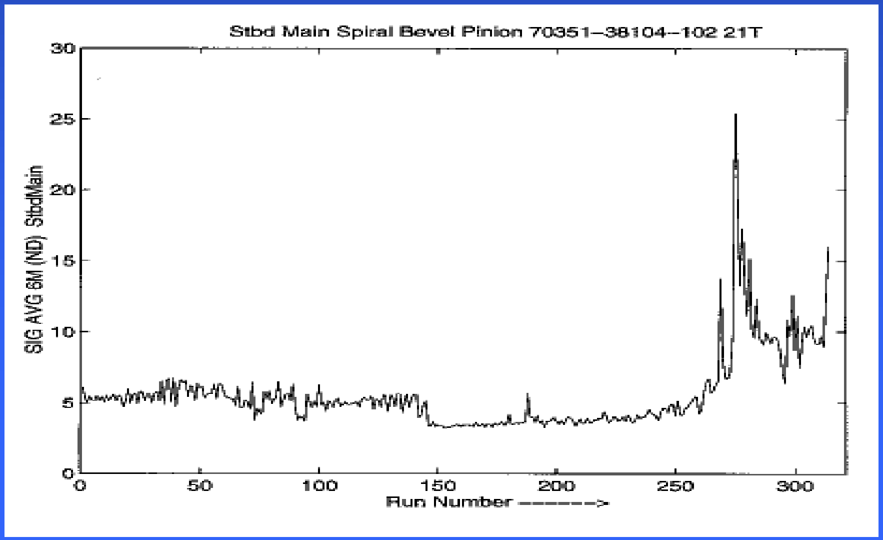
Front view of web crack and partial tooth removal

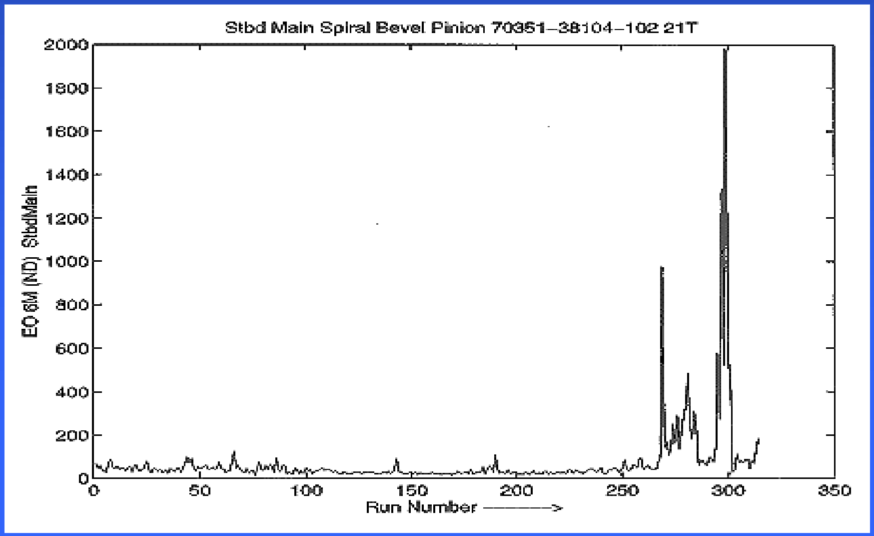
Intermediate Gearbox Root Bending Fatigue Decision

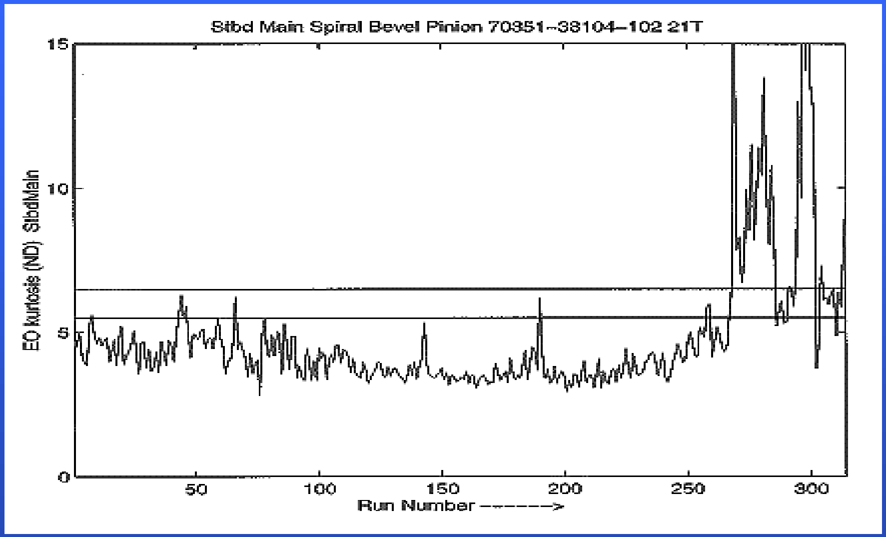
- Crack propagation through tooth and gear web to the bearing diameter.
- HIDS classical, model based diagnostics detected fault 3.5 hours before raw FFT.
- HIDS diagnostics demonstrate early detection of gear tooth cracks. Can assist in avoidance of gear failure and aircraft loss.
- These types of data sets are invaluable for exploring and developing prognostics and accurate useful life remaining predictions.
- This data set is being shared with industry.

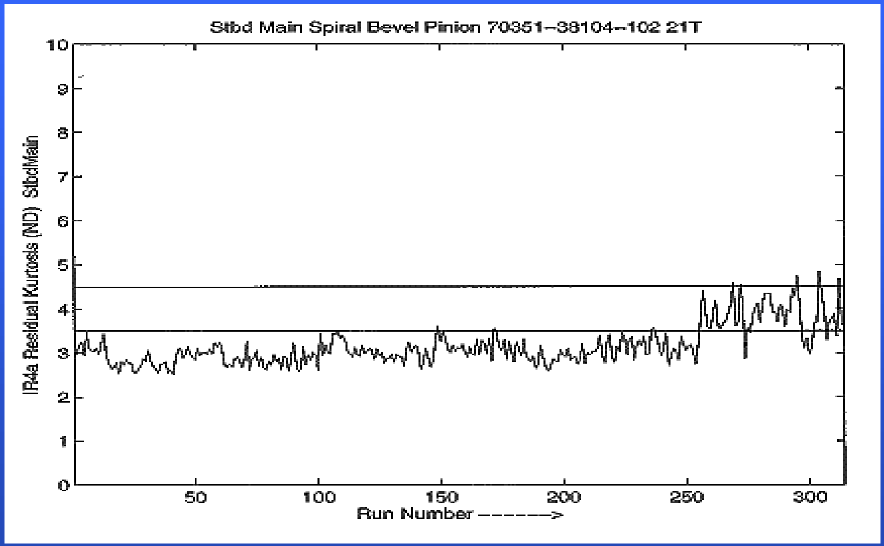
Main Xmsn Input Pinion Root Bending Fatigue Diagnostic Indicator Suite

Main Xmsn Input Pinion Root Bending Fatigue Diagnostic Indicator Suite



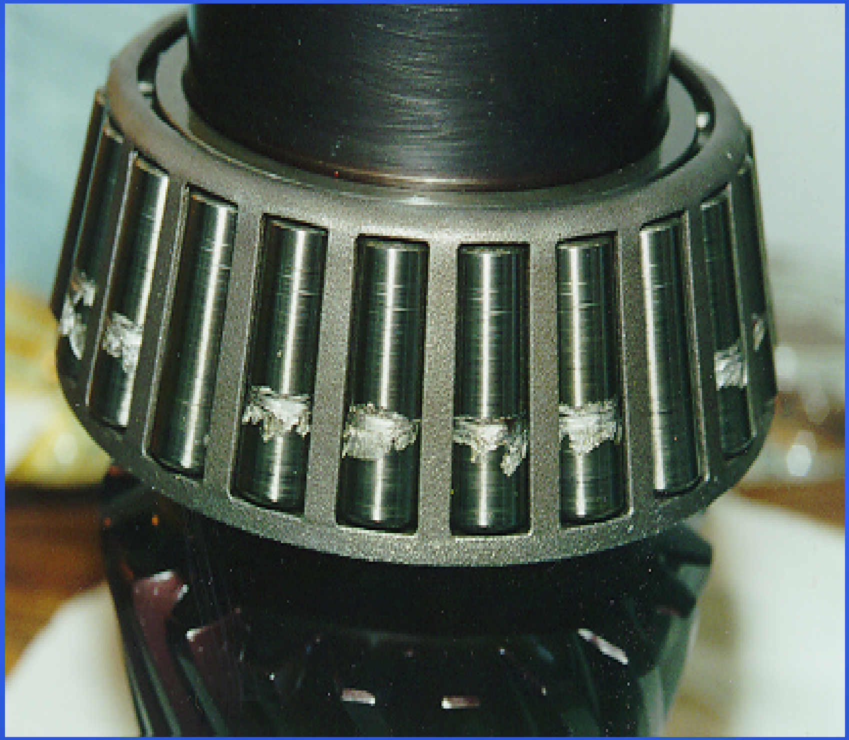






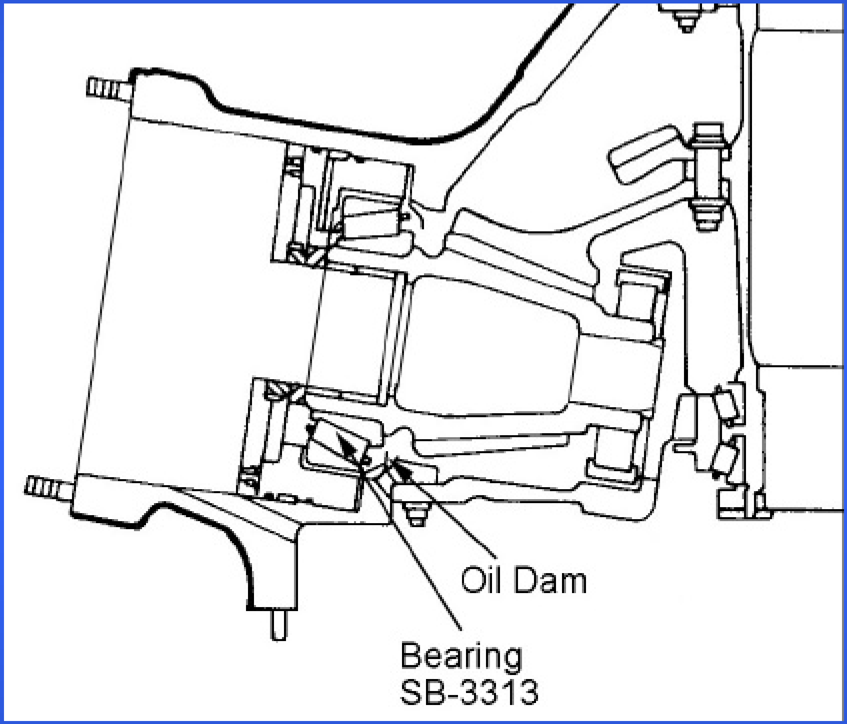
Aircraft BUNO 176
Main Xmsn Timken Brg

- Data acquired on-aircraft and test cell
- All vibration analysis results identified stbd input Timken as faulted part
- Teardown inspection confirmed vibration analysis results



Main Xmsn Timken Brg

- Chip generation did not reach xmsn removal requirement
- HIDS team recognized oil dam could harbor debris; danger of bearing locking-up and wearing through pinion
- Removal strongly recommended



Prognostics Case Example
Main Xmsn Timken Bearing

The Failure Case

- Unique, one-of-a-kind failure
- No historical failure information

Managing The Failure

- Model Based Diagnostics identifies failure without prior case examples
- Utilize FMECA information to optimize diagnostics/prognostics
  - Loss of lube oil dam inhibits debris migration
  - Critical drivetrain component
- Prognostics is difficult
  - Data Fusion/Advanced Reasoners are enabling technologies, but:
  - No failure progression information

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Prognostics Case Example
Integral Raceway Pinion

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The Failure Case

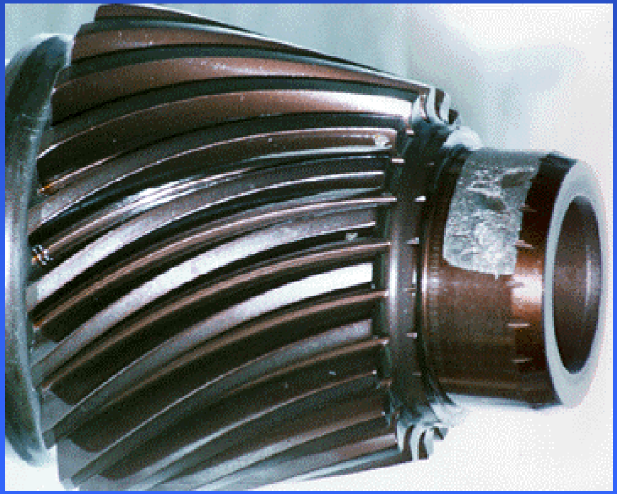
- Common, repeatable failure mode
- Progresses from localized fault into larger one that encompasses large portion of race

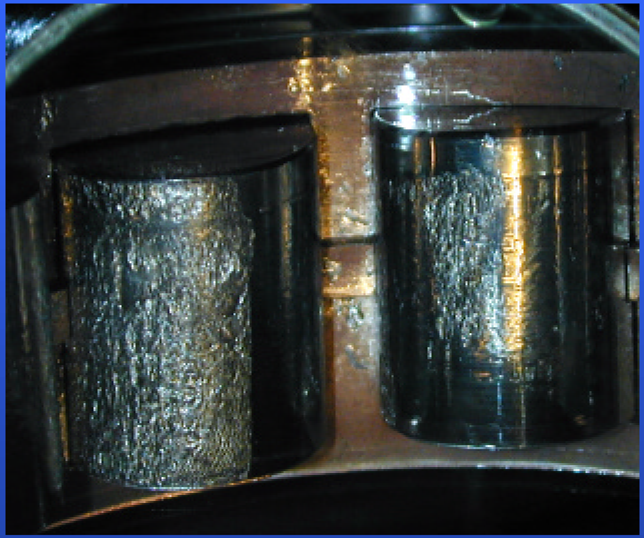
Managing The Failure

- Localized defect indicators detect initial fault, then it appears to self-heal
- Statistical indicators identify the defect as localized indicators taper off
- Prognostics tracks the progression, enabling:
    - Safe operation if the asset is mission essential
    - Field repair of known, accessible component to minimize secondary damage, repair cost and complexity

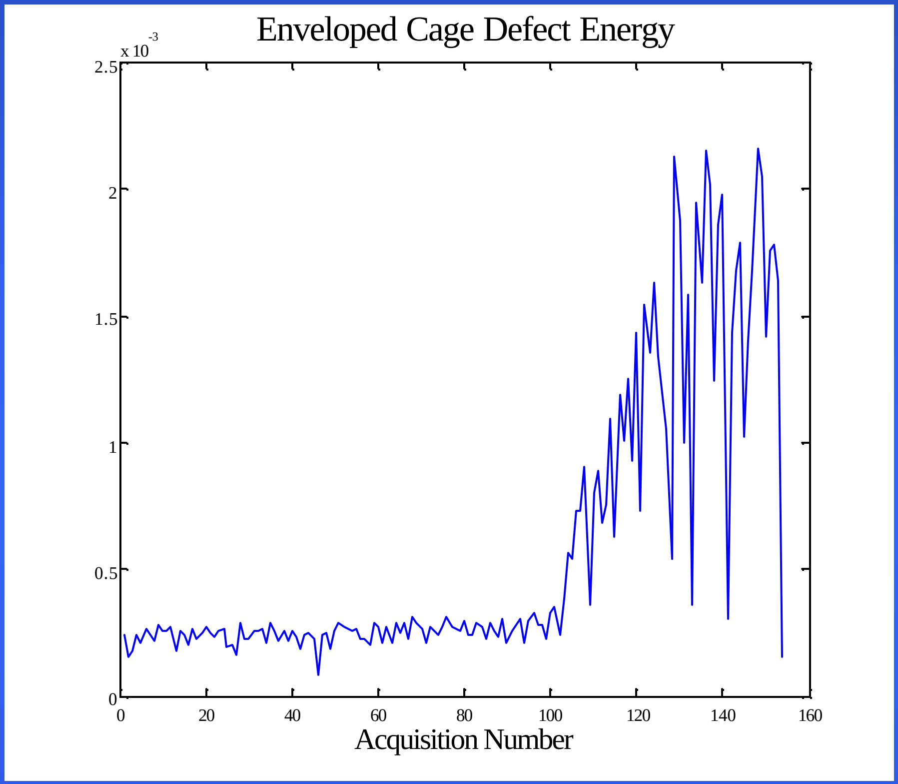
Rolling Element Failure
Blackhawk Qual Test

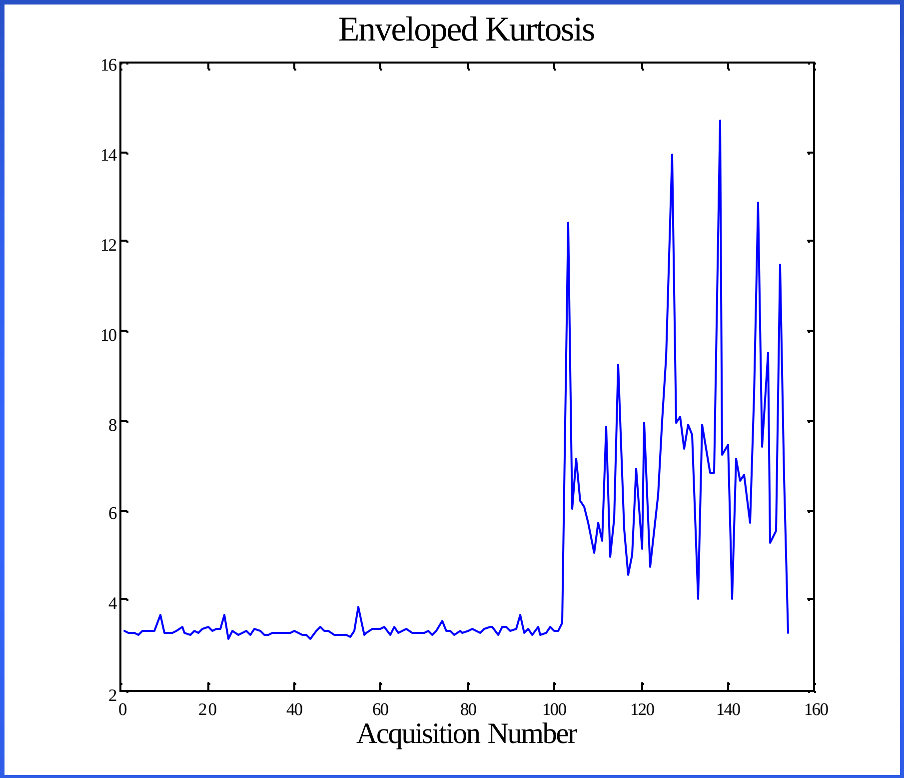
- Tested fleet rejected SB2205 roller bearing integral inner race with severe spall prior to Blackhawk qual test
- Replaced faulted part with serviceable part and inspected rollers
- No signs of damage until 130 hours
- Chip light indication shortly after startup
- Within 3 hours, diagnostic algorithms can detect root cause
- Rolling element damage from contact with spalled inner race





HTTF Bearing Fault Propagation Diagnostic Indicators



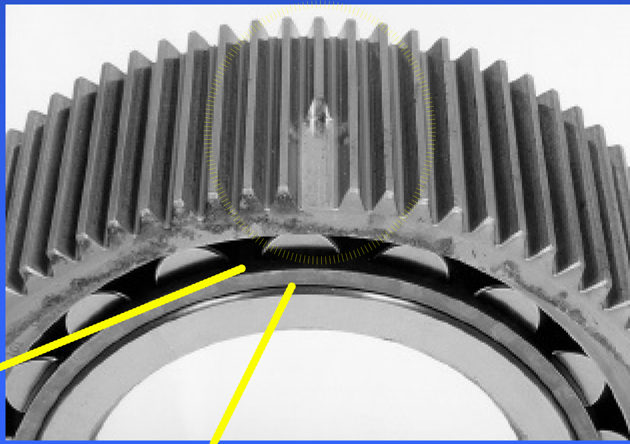


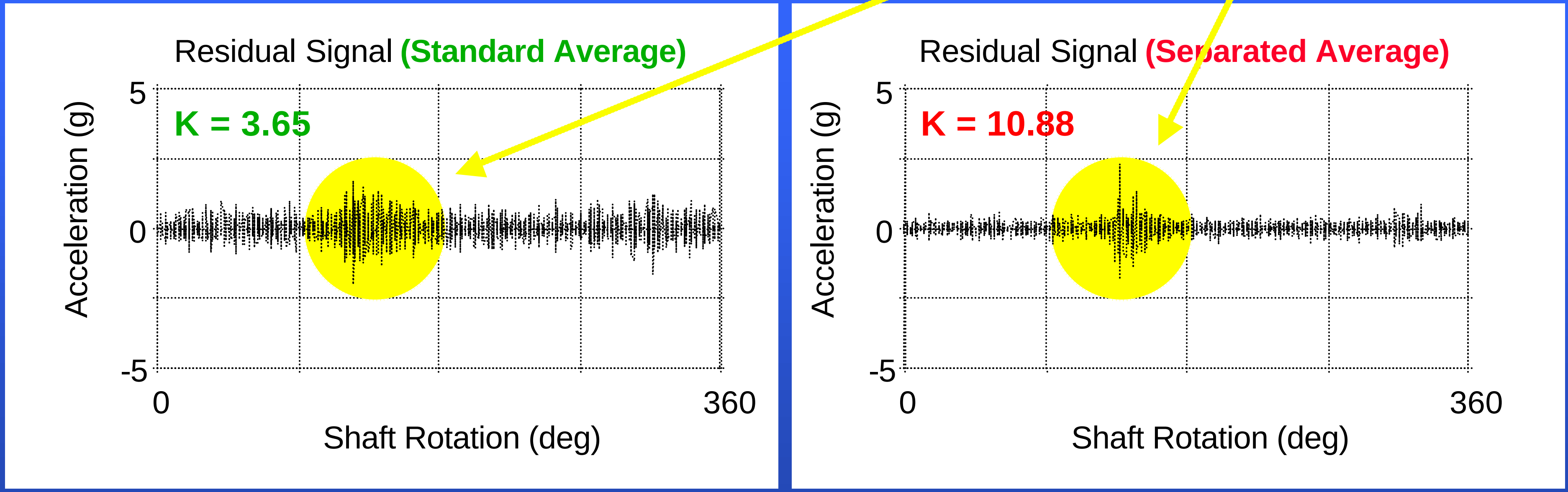
- Captured complete failure progression over several hundred hours
- Pinpoint defect is SB2205 Cage/Rolling Elements
- Indicator response is robust

SH-60 Seeded Planet Fault

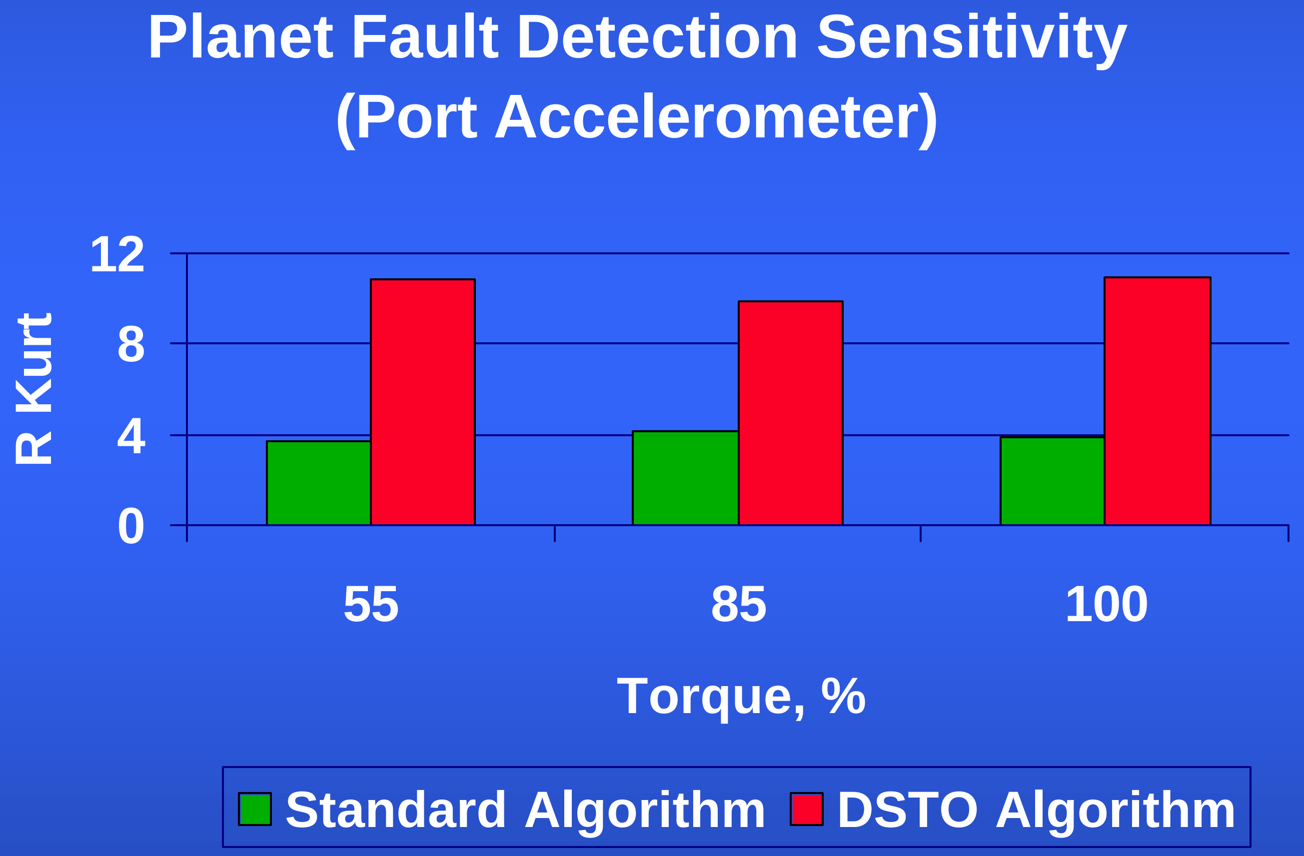
- USCG H-65 Dolphin sun gear failure heightened interest in the planetary gear system
- Unique and challenging detection requirements
- Gross fault - Removed part of tooth
- Fault more easily detected with planet separation algorithm from **DSTO** Australia

Planet Gear Fault



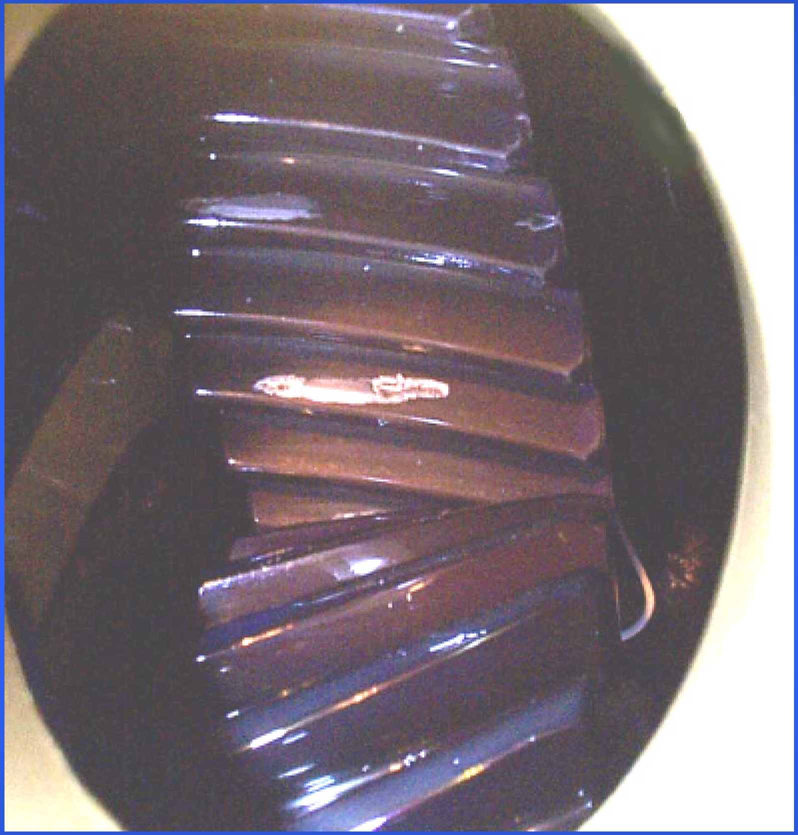


DSTO Planetary Algorithm



Input Module
“1/2 Gear Mesh” Anomaly

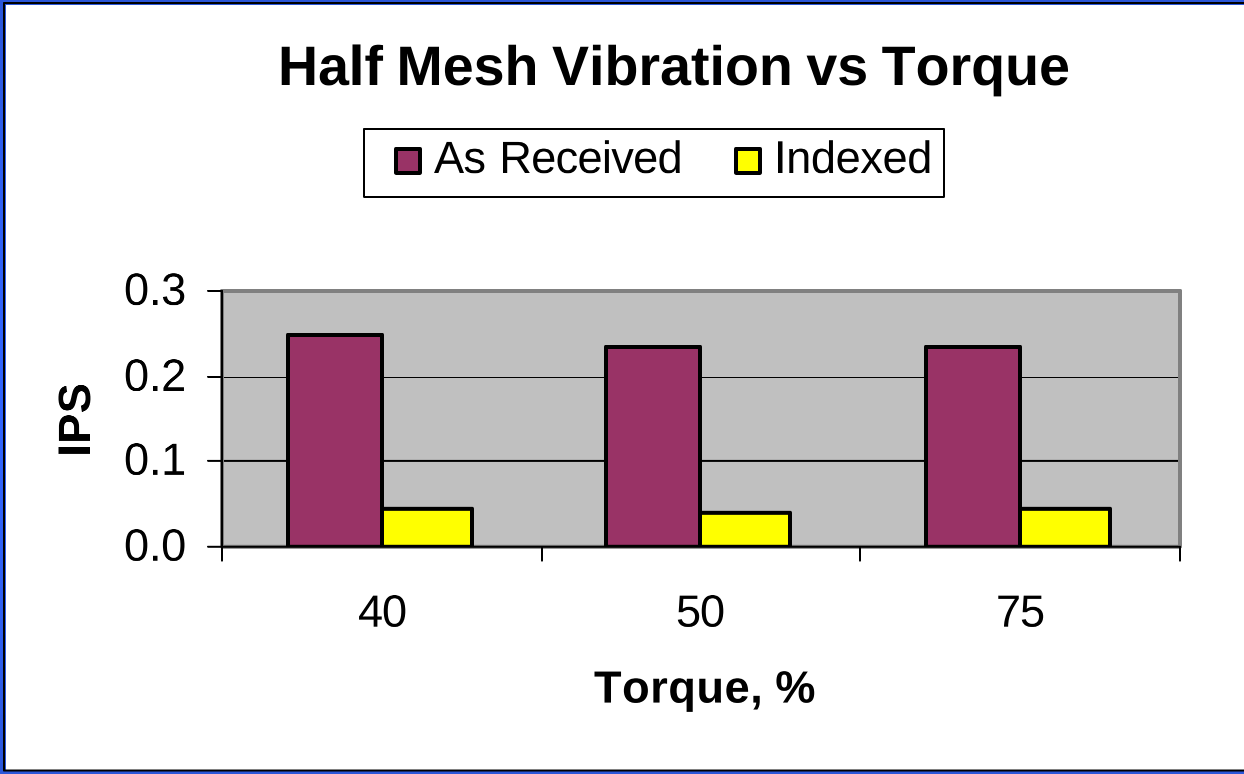
- Engines repeatedly removed from H-60/S-70 aircraft for Torque indication problem.
- Gearmesh anomaly in input module exciting and damaging T700 PT shaft.
- Several fleet removed suspect modules tested and fault identified.
- Most half-mesh input modules in serviceable condition.
- One module with high time had two significant spalls on the same tooth, indicating half-mesh potential for damaging gear teeth.



USCG Fleet Input Module

Input Module
"1/2 Gear Mesh" Anomaly

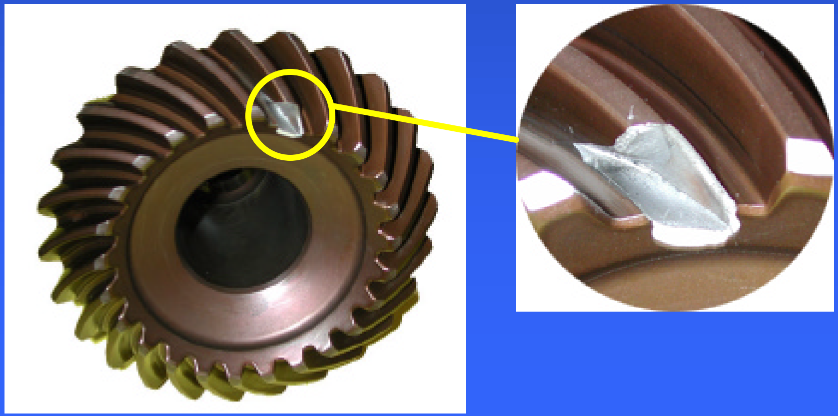
- Potential for damage highlights importance of early detection.
- AIR 4.4 recommended remedy of re-indexing pinion/gear for serviceable assets, based on test data.
- Parts tagged for replacement when input module is removed for other cause.
- Reason for removal AND secondary engine damage effectively and safely eliminated.
- Shipboard ground procedure developed.

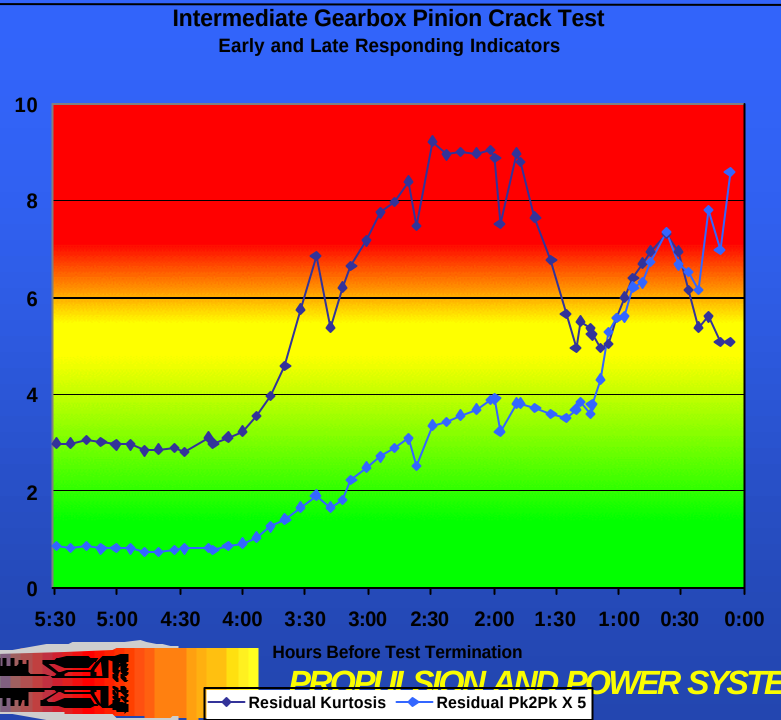


Gear Tooth Crack Prognostics Test

- **Procedure**
  - Create stress riser in gear to induce crack
  - Run gear at Pax River HTTF until just before catastrophic gearbox failure
  - Inspect at regular intervals
  - Attempt to:
    - Measure crack size and determine crack propagation rates
    - Predict remaining useful life
    - Obtain better understand the physics of failure for this component

- Crack propagated the entire length of the tooth, through the web. Portion of tooth broke off at end of test.





- **Objectives**
  - Perform NDI at regular intervals to quantify physical condition
  - Document incipient fault to failure progression characteristics vs. detection indicator activity levels
  - Use data for preliminary life remaining timeline predictions
  - Compare prediction results with Fracture Mechanics Models
  - Expand Knowledge base of seeded faults and procedures for developing Prognostics

Conclusions

- Powertrain diagnostics are available and work
- Prognostic capabilities provide the fleet and logistics community with great benefits
- Seeded fault tests are invaluable in establishing:
    - Alarm thresholds
    - Failure progression rate characteristics
    - Accurate remaining useful life predictions
    - A low risk and safe fleet implementation program
- Failure propagation tests provide:
    - An understanding of failure progression dynamics
    - Reduced uncertainties caused by discrete step changes
    - Increased safety and reduced false alarms
- HTTF is an indispensable IMD HUMS and fleet support asset
- Further development of model-based analysis, reasoners, and data fusion techniques is required

HTTF Planned Efforts

- IMD Seeded Fault Testing - Emphasis on Epicyclic
- Gradients of severity for several fault types
- Fleet rejected components
- Qualification of Alternate Gearbox Dynamic Components (ongoing)
- Wireless / MEMS Transducers
- Enhance Multivariate Analysis, Data Fusion, and Reasoner Techniques
- Explore boundaries of prognostics through understanding failure progression characteristics and physics of failure
- Aggressively pursue prognostics technologies and their implementation in existing health management systems